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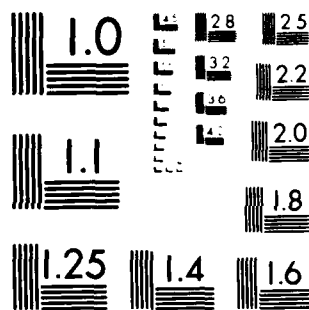12-83
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NATIONAL BUREAU OF STANDARDS 1963 A

AFWAL-TR-83-4080

ION DEPOSITED CARBON COATINGS

Gulf and Western
Applied Science Laboratories
335 Bear Hill Road
Waltham, Massachusetts 02154

July 1983
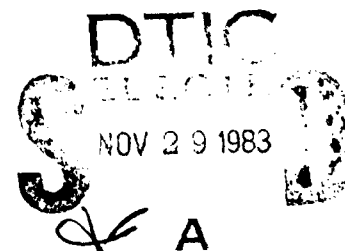
Final Report for Period: February 1979 - February 1983

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Materials Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for
publication.

ROBERT L. RAPSON, Chief
Structural Materials Branch

FOR THE COMMANDER

FRANKLIN D. CHERRY, Chief
Nonmetallic Materials Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this report, reproducible technique of ion deposition of carbon of uniform thickness (6) onto polycarbonate was demonstrated and study was done on coated polycarbonates. The coating has improved the abrasion resistance but it did not function well under environmental testing and some chemical exposures (anti-icing solution and detergent solution) which caused the weakening of adhesion bond strength leading to delamination of the carbon coating.

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1.0 OBJECTIVE

The overall objective of this program is to demonstrate a system capable of reproducibly coating polycarbonate plastic sheet with ion deposited transparent carbon. The carbon coatings are to be characterized on the plastic sheet for potential use as a durable, abrasion resistant coating for windshield and canopy assemblies.

2.0 SCOPE

This program involves the deposition of carbon onto
polycarbonate substrates using an energetic plasma technique. The
deposited coatings have been characterized for uniformity of
thickness and composition, adhesion, and resistance to chemical
and humidity environments. The initial part of the program
involved deposition using existing equipment (hereafter referred
as the "preliminary system"). An apparatus was then assembled
which was capable of producing significantly larger areas (up to
25 cm x 8 cm). This system is referred to as the "improved
system".

3.0 BACKGROUND

Polycarbonate offers many advantages as a transparent
material for windshield and canopy assemblies. However, it
suffers from abrasion resistance as well as chemical attack. The
technique discussed in this report is designed to solve these
problems.

Applied Science Laboratories (ASL) has had several years
experience depositing transparent diamond-like carbon films of the
type produced for this program. [1-12] Notable among the
properties are hardness and inherent integrity to chemical attack.
Others have verified the properties we have reported. [13] A thin
coating of such a material may offer a solution to allow the use
of polycarbonates as canopy and windshield assemblies.

4.0   COATINGS DEPOSITION

Two versions of the coating system for ion deposition of carbon were used in this program.   The first system referred to as the preliminary system was the coating system in existence at the time of contract award.   As part of this effort, this preliminary system was modified to produce larger, more uniform coatings.   The following sections detail these systems as well as describing the coatings produced by them.

4.1   Preliminary Coating System

The preliminary coating system consisted of an ion beam source mounted in an 40 cm diameter glass bell jar.   The ion source is depicted in Figure 4.1, showing the principle components.   Ions were extracted from the DC excited magnetron in the lower portion of the drawing which was feed with a gas mixture of 90% methane, 10% argon.   Ions were extracted from the plasma rich zone using an extraction grid which had a potential of -2000V applied.   Following this was a deacceleration grid which was maintained at -100V.   The grid extraction configuration is of the Kaufman type, using an array of apertures.   The extraction grid and substrate were maintained at the system pressure of approximately 8×10^{-4} Torr.   The substrate which could be
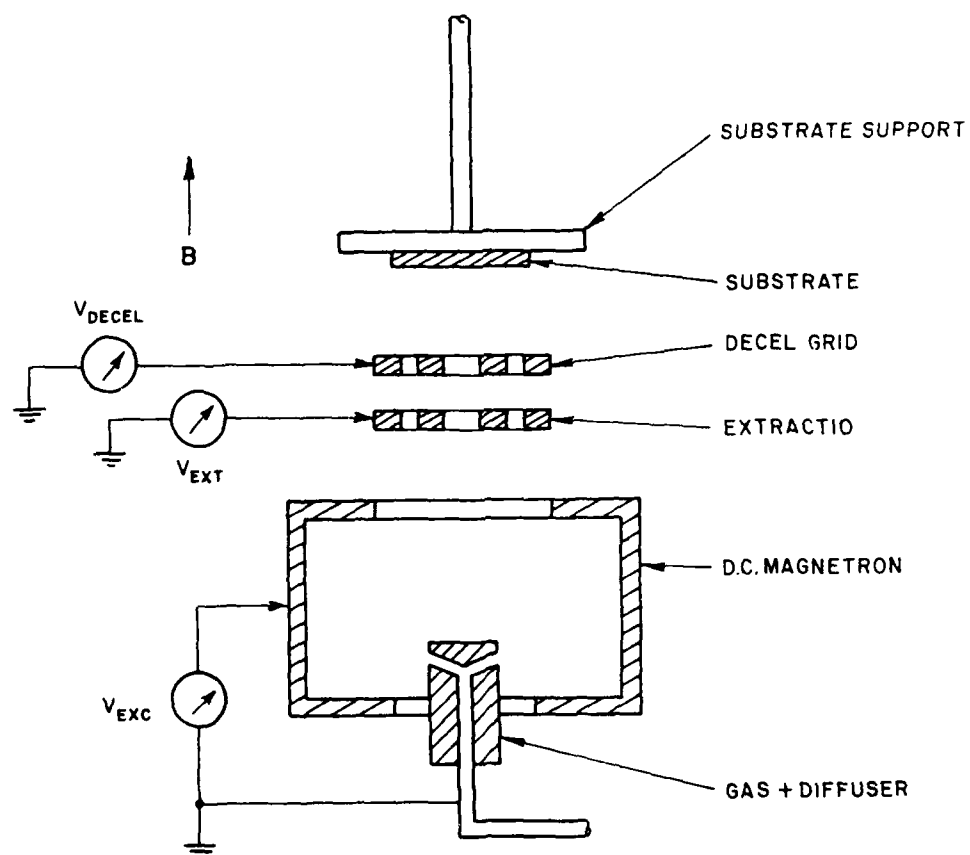
Figure 4.1   Cross-Section of the Preliminary Deposition
System Showing Principle Components

effectively coated with this system had a maximum diameter of about 2.5 cm. No substrate bias was applied. The substrate charged under electron bombardment to maintain an average potential of about -50V. Also applied during deposition was an axial magnetic field used to collimate the plasma discharge and beam.

For operation, the plasma chamber was ignited by applying the excitation voltage. The beam was then extracted and allowed to impinge on the substrate for a period of 20-30 minutes to produce the desired coating. At the end of this time, the sample was allowed to cool prior to removal from the chamber.

4.2 Coatings with the Preliminary Coating System

Using the preliminary coating system, a total of 77 coating runs were performed to generate enough samples for evaluation by the contractor as well as for off site characterization. Samples made during coating runs 1 to 61 were retained for testing at Applied Science Laboratories (ASL), while coating runs 62 to 77 were shipped to Wright-Patterson as samples for evaluation.

The polycarbonate sheets were supplied by the sponsor in the form of a 4 ft. sq. sheet of polycarbonate as well as a 1 sq. ft. piece with a pressed polished surface. The larger sheet was used for set up and initial inhouse characterization, whereas the 1 ft.

sq. sheet was used for test specimens.

One factor considered throughout this program is the substrate temperature rise, since degradation under vacuum conditions may occur to the front surface at lower than expected temperatures, due to the effects of ionizing radiation and electron bombardment. With the preliminary system, the temperature rise measured on the 1/4" thick polycarbonate sheets was found to be approximately 50°C after one half hour of operation. The actual time required for film thickness is a function of deposition rate. It was found that this period of one half hour is capable of producing a 0.6 micrometer thick film. Consequently, the bulk of the coatings made for characterization both onsite and by the sponsor were 0.6 micrometers thick. It appears that substrate temperature rise for samples of this size appeared to be no problem. Substrate cooling however, may become a problem for significant longer runs or larger areas.

Sample preparation was performed by saw cutting the samples from the sheet supplied, then by cleaning with isopropanol. After insertion into the vacuum chamber and mounting on the substrate holder, the chamber was pumped down to less than 4×10^{-4} Torr pressure. The samples were then cleaned by a five minute period of argon ion bombardment. The system was then switched over to a one half hour deposition resulting in the 0.6 micron thick coatings. The coatings were uniform to within 0.1 microns over

approximately 2.5 cm diameter. Samples for testing were indicated
by an arrow where the coating portion is specified.

Documentation for items shipped to the sponsor for off site
evaluation are listed in Section 5 of this report.

4.3 Improved Coating System

Following the completion of coatings made with the
preliminary system, the coating chamber bell jar assembly was
modified to incorporate a carbon ion source capable of coating
8 cm diameter areas with reasonable uniformity. A cross-section
of the improved deposition system is shown in Figure 4.2,
depicting principle components. A hollow cathode magnetron was
again used for the improved system with the exception that it was
of larger diameter and was excited with an RF potential coupled to
the magnetron chamber. An extraction electrode was provided for
ion extraction as well as plasma containment. An axial magnetic
field was applied similar to that used for the preliminary coater.
For the improved system, a bias substrate holder was provided to
accommodate 8 cm diameter specimens along with a moveable
substrate carriage which allowed one dimensional scanning of the
substrate.
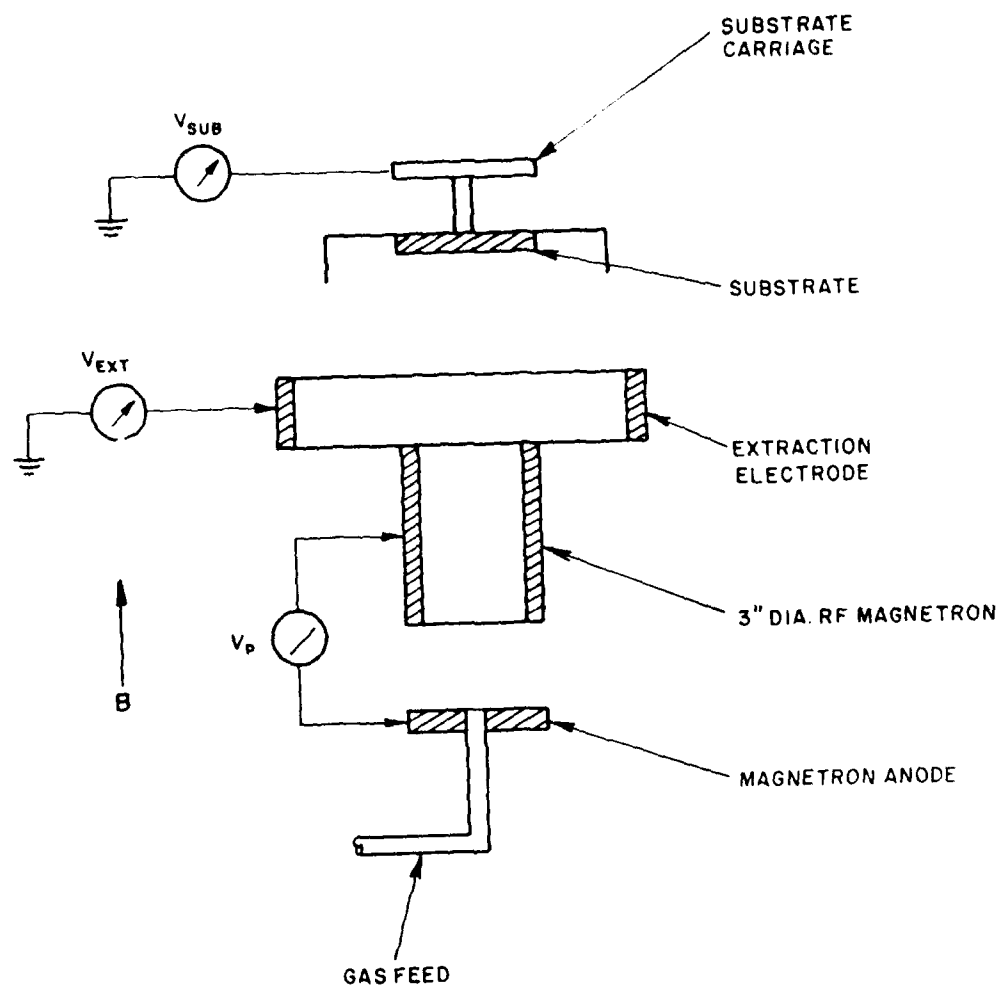
Figure 4.2   Cross-Section of the Improved Deposition
System Showing Principle Components

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4.4 Coatings with the Improved System

For this series of coatings, a new supply of polycarbonate sheet was sent. This sheet was identified as SL-3000 received 22 May 80 and it was submitted as four, 1 ft. sq. pieces. The sheet provided was in the same nominal 0.6 cm thickness as the previous material tested. A series of nineteen deposition runs were performed with this material using the improved coating system to produce samples for on-site evaluation, as well as for evaluation by the sponsor. Sample preparation was the same as that used for the preliminary coatings, including the cleaning and argon ion bombardment prior to coating. Due to the relatively larger coated area, sheets measuring 8 cm x 22 cm were put into the coating chamber and scanned along one axis until a coating of approximately 0.6 micrometers in thickness was deposited. At this point the sample was allowed to cool in the chamber prior to venting and removal of the coated materials.

During deposition, a chamber pressure of approximately 8×10^{-3} Torr was maintained with an applied substrate potential of -40 volts corresponding to the anticipated surface floating potential. After removal from the coating chamber, the samples were cut up into the shapes required for testing. Samples which were submitted to the sponsor for off-site evaluation are documented in Section 6 of this report.

5.0 COATINGS CHARACTERIZATION

Contained in this section are the methods and results of coatings analysis performed on site as well as any results reported from evaluation by the sponsor.

5.1 Composition

The composition of the coating on polycarbonate was analyzed using several techniques. Initial attempts at characterization were made using infrared transmission to compare the absorption characteristics of the polycarbonate with that of the polycarbonate containing a 0.6 micrometer coating. Results of this characterization were negative due to the high absorption of the polycarbonate which inhibited transmission of sufficient light to produce an absorption spectrum. This was true for the coated as well as the uncoated samples.

In an attempt to characterize and compare the surface morphology of the coated versus uncoated polycarbonate samples, scanning electron microscopy was used as a technique. The samples were prepared by depositing a 200Å thick gold replication coating to allow surface imaging. The samples identified as 3360-2-10 was 0.4 micron thick, coated with the preliminary deposition system. The sample consisted of a 3" diameter disk which was half coated

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with ion deposited carbon, the other half was masked. This sample was cut up for analysis so that adjacent sections could be analyzed side by side. The analysis was performed on an ISI-60 System at 20,000x magnification. The results of this work are illustrated in Figure 5.1, contrasting the coated versus uncoated surfaces. The longer line on each photomicrograph is 1.0 microns. An obvious difference between the two is that the coated sample appears to be much smoother than the uncoated sample.

5.2   Thickness and Uniformity

Film thickness for this work for both deposition systems was measured by counting optical interference fringes. These fringes build up due to the presence of the higher index coating on the polycarbonate substrate. Polycarbonate, which has a refractive index of about 1.59, had the ion deposited carbon coating with a refractive index of about 2.4. The coating produced quarter wave interference fringes. The thickness in any region can be calculated by the following equation:

$$4n_ct = \lambda$$

where n_c is the refractive index of the coating, t is the sample thickness, and λ is the incident wavelength used for measurement. Using this equation the film thickness can be estimated by counting fringes starting from the extreme edge of the coated surface. In this way, a film thickness of approximately 0.6 + 0.1

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├─────┼─────┤ 1.0 μm
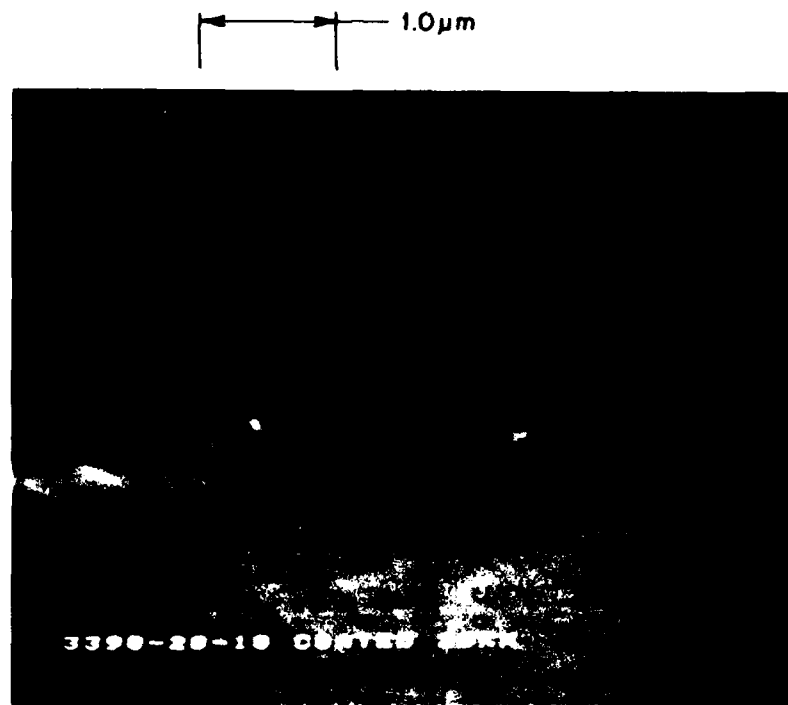
3440-2-10   0.6 μm CARBON COATING

3440-2-10 UNCOATED

Figure 5.1   20,000x SEM Photomicrographs of Polycarbonate Surfaces
With and Without a 0.6 Micrometer Carbon Coating

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micrometer was maintained.

5.3 Adhesion

This section describes the technique used to measure the bond strength between the coating and the polycarbonate substrate using a pull test as depicted in Figure 5.3.1 and the accompanying photograph of the apparatus, Figure ..3.2. The apparatus is used to apply a constantly increasing load to a post bonded with epoxy to the coated substrate. The epoxy bonded area is approximately 1 cm square to provide a useful sample surface for comparative testing. As the load is increased at a rate of approximately 100 psi per second, the output from the load cell and pressure transducer are monitored with a chart recorder. At the point of break, the break load is recorded. The bond strength is calculated based on known areas of the hydraulic cylinger and the measured area of bond failure. Testing was performed at nominal laboratory atmospheres, $23° \pm 5°C$ and $50° \pm 10\%$ relative humidity. The results of these tests indicated on the control specimens that all failures occurred between the epoxy and the coating. Failure of the bond between the coating and the substrate had not occurred in any of the cases for this group of as-coated specimens. The results for the as-coated polycarbonate specimens is outlined in Table 5.3.3 for both the preliminary deposition and the improved deposition system. Results of bond strength measurements after

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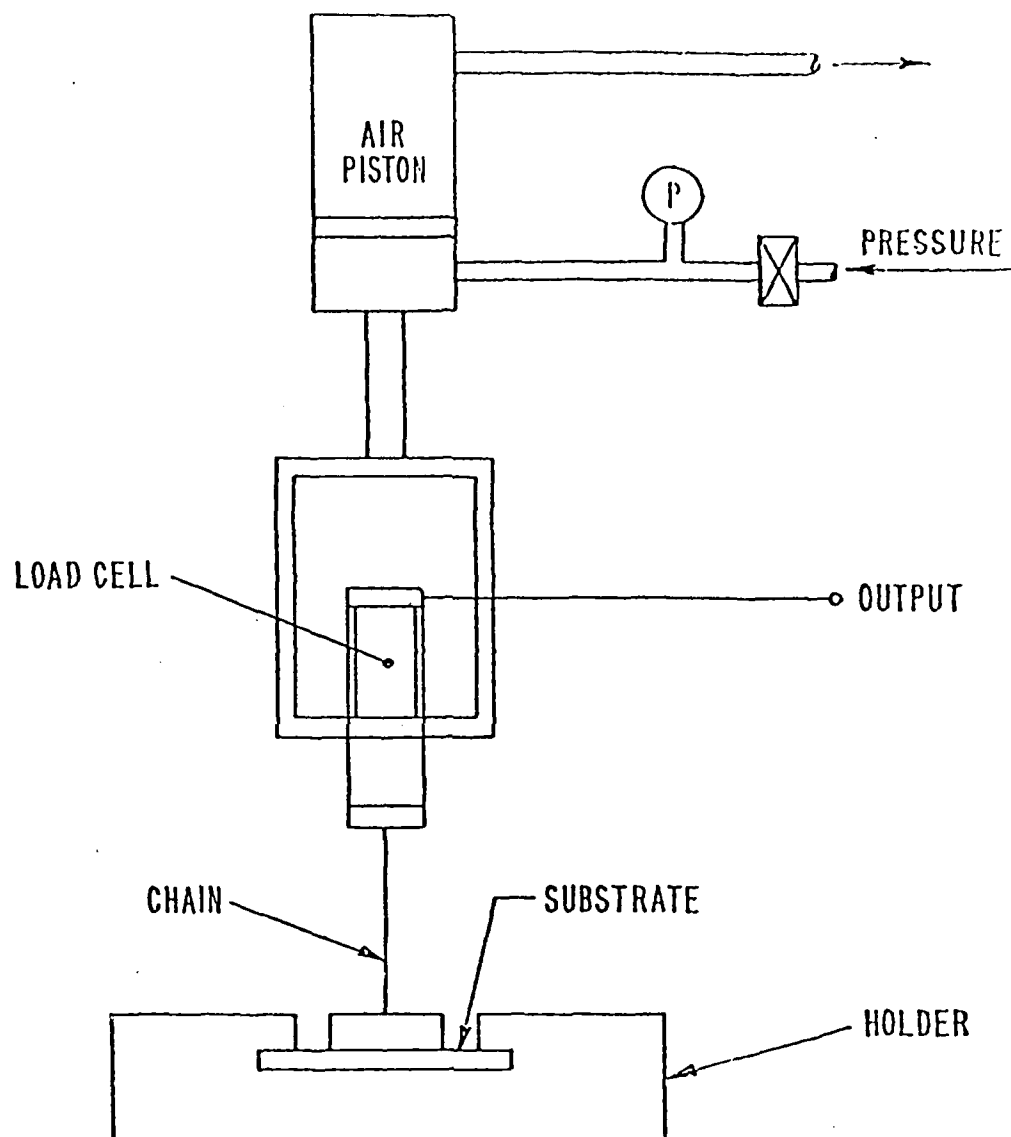
Figure 5.3.1 Tensile Pull Test Apparatus
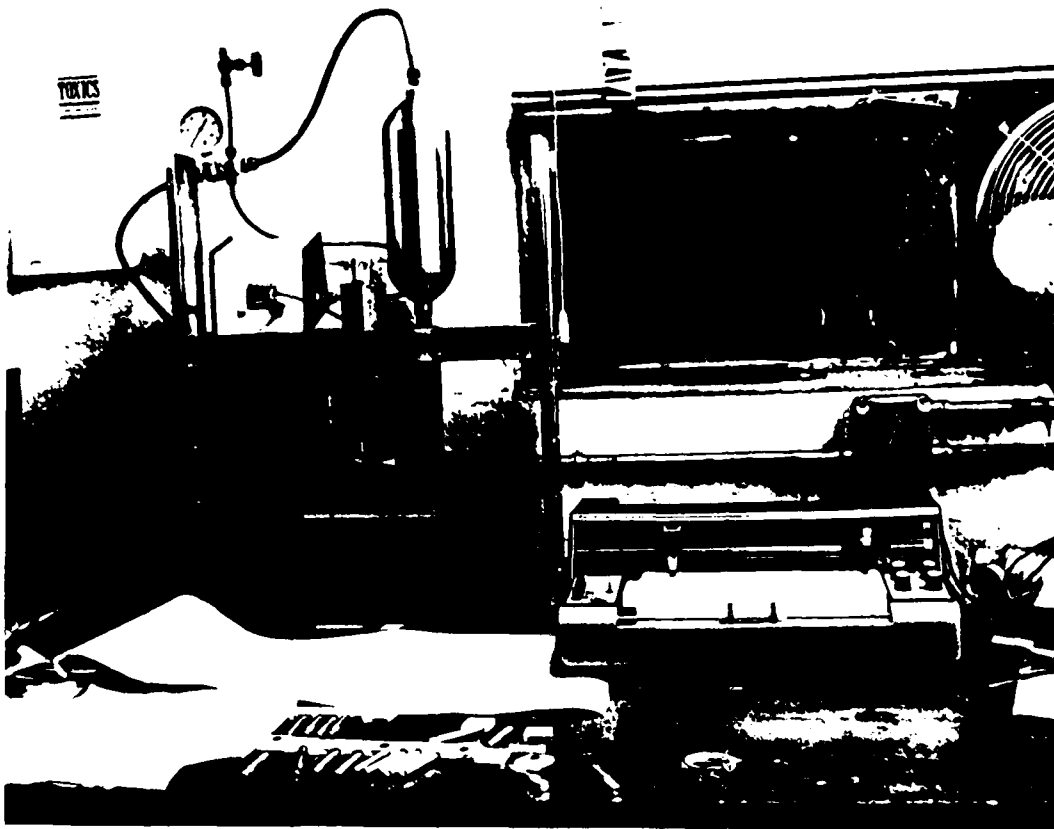
Figure 5.3.2   Photograph of Tensile Pull Test Apparatus

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aging and exposure conditions are discussed in the appropriate sections which follow.

5.4 Optical

Samples made with the preliminary deposition system were characterized in a series of tests for infrared transmission, ultraviolet-visible transmission and reflectance in the visible region. Three sets of samples were prepared:

1. Sample #3440-C-10, was polycarbonate coated with 0.8 micrometers of carbon on one side.

2. Sample #3440-2-12, was polycarbonate coated with 0.2 micrometers of carbon on one side.

3. Sample #3440-2-12 Reference, was an uncoated polymer reference sample.

Infrared transmission measurements were attempted in the region from 4000-670 cm^{-1}. The two coated samples in the reference are essentially opaque in this region, so no significant information could be obtained. In the ultraviolet-visible region from 800-200 nm the samples have a minimum tranmission relative to air of 19% at 390 nm. Relative to reference sample no. 3, samples one and two have a minimum transmission of 90.5% and 94.3% at about 400 nm. A copy of the ultraviolet-visible spectrum is reproduced in Table 5.4.1. The results of the reflectance tests were made for each sample and are documented in Table 5.4.2 of

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COATING SYSTEM	SUBSTRATE	CONDITIONS	MINIMUM* BOND STRENGTH (psi)
Preliminary System	Polycarbonate sheet, first shipment	Tested @ R.T. <7 days after coating	(580) (650) (780) (410) (300) ___ (544) Avg.
Preliminary System	SL-3000	Tested @ R.T. <14 days after coating	(1190) (1070) (750) (940) (1760) (1570) ___ (1213.3) Avg.

* All failures are between the coating and the epoxy. The coating didn't delaminate from the Polycarbonate.

Table 5.3.3 Bond Strength Results for 0.6 Micrometer Ion Deposited Carbon Coatings on Polycarbonate

this report. The changes in reflectance are primarily dominated
by the interference characteristics of the coatings at these
thicknesses.

After the coatings were completed with the improved system, a
series of optical transmission tests were made on the as-coated
samples as well as samples exposed to 1,5,10 and 20 days of
humidity. The results of these tests are listed in Table 5.4.4 of
this section. As noted in the data, no significant change in
transmission occurred over the visible spectrum after humidity
exposure.

5.5 Environmental Exposure

The purpose of the tests in this section is to determine the
effects of materials and events which may occur on the coating
surface throughout its use cycle. Coated and uncoated test
specimens were exposed to accelerated, high temperature, high
humidity aging, UV exposure, and exposure to a series of
chemicals.

Elevated temperature high humidity exposure was performed by
placing the prepared and coated specimens in a humidity chamber
maintained at $120° \pm 2°F$ and $95° \pm 3\%$ relative humidity. Samples
were withdrawn from the chamber at intervals of 1,5,10 and 20 days
for evaluation, based on appearance, optical properties and

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200 nm

240

320

400

480

560

UV - Vis Spectra

CURVE	SAMPLE BEAM	REFERENCE B!!
A	8000Å Carbon on Polycarbonate (#3440-C-10)	Air
B	8000Å Carbon on Polycarbonate (#3440-C-10)	Polycarbonate (#3440-2-12 Ref)
C	Air	Air

640

720

13464

800 nm

(A)   (B) (C)
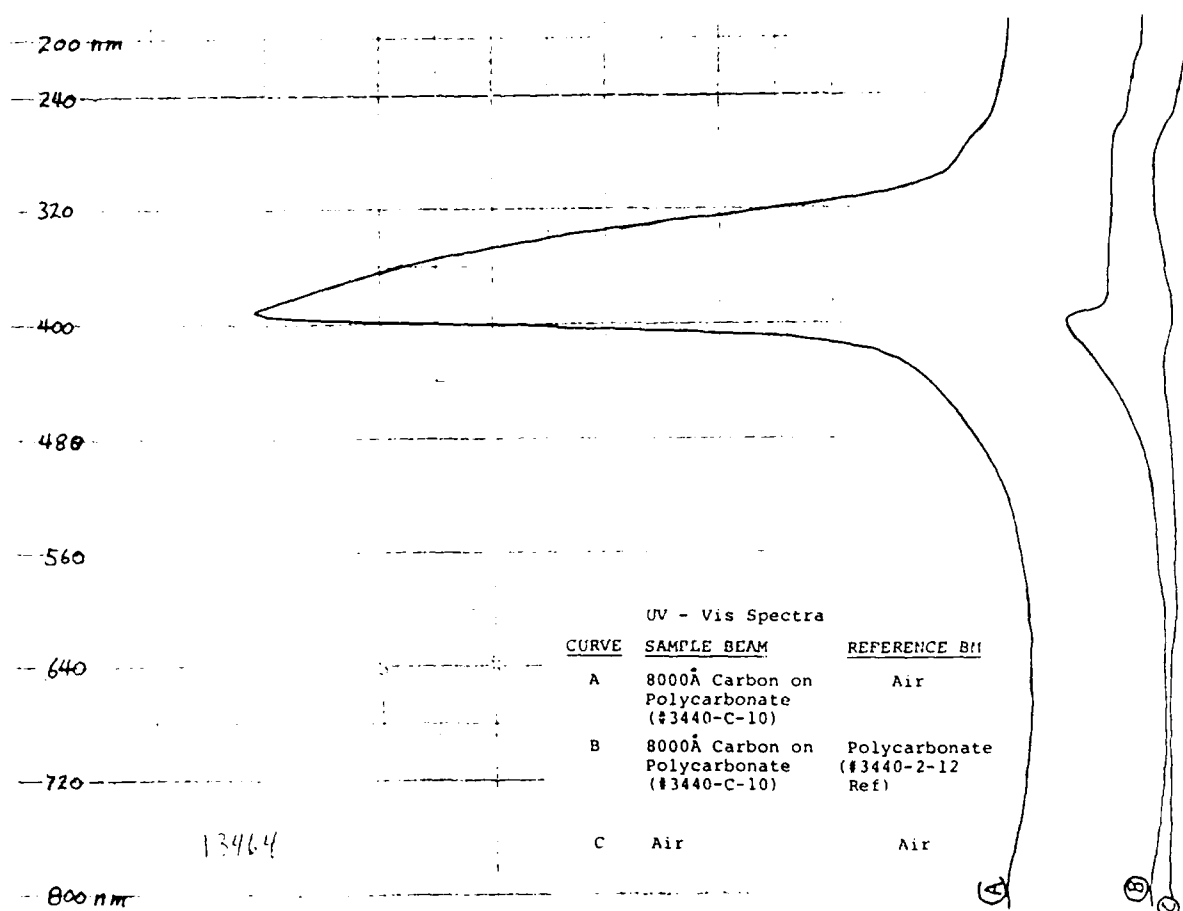
Figure 5.4.1   UV-VIS Spectra for 0.8 Micrometers of Carbon
on Polycarbonate

200 nm

240

320

400

480

560

640

                                    UV - VIS Spectra

CURVE	SAMPLE BEAM	REFERENCE BEAM
A	2000Å Carbon on Polycarbonate (#3440-2-12)	Air
B	2000Å Carbon on Polycarbonate (#3440-2-12)	Polycarbonate (#3440-2-12 Re)

720

13464

800 nm
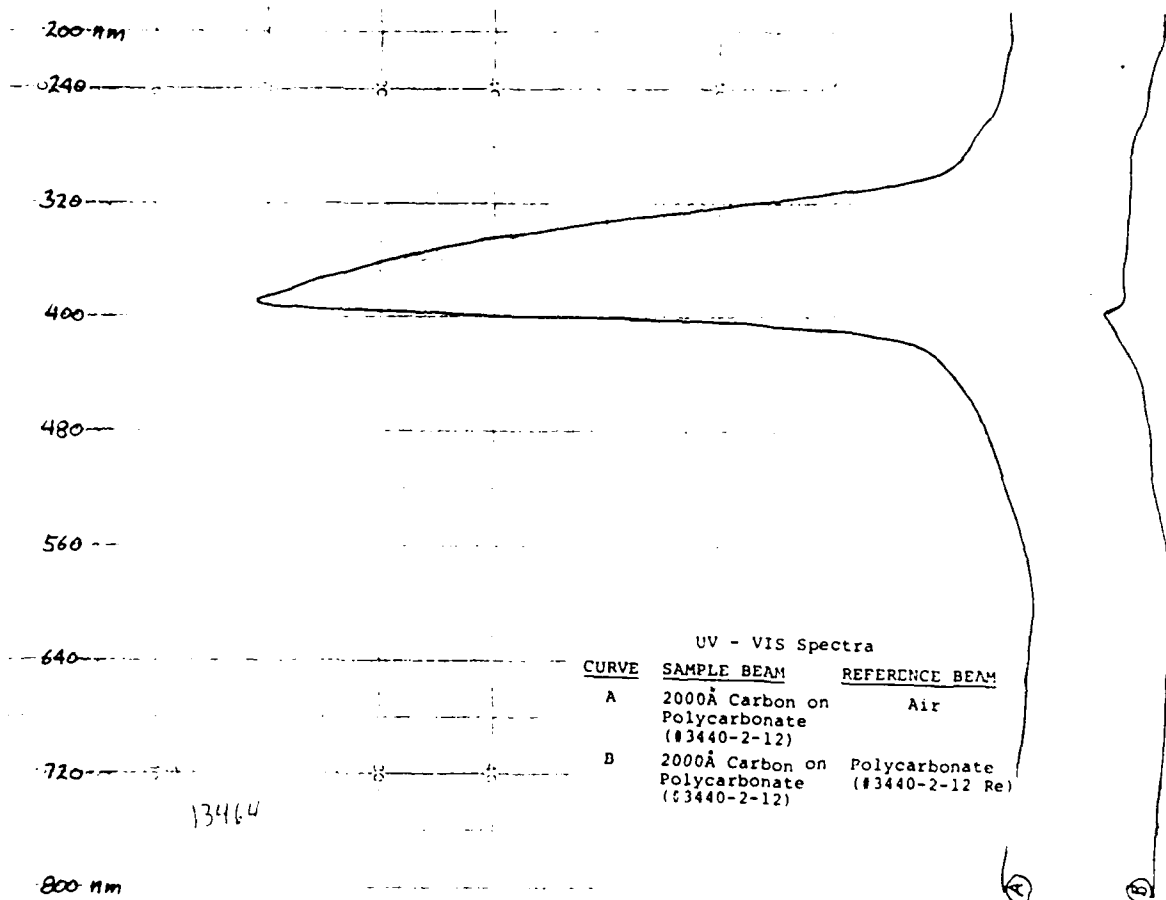
Figure 5.4.2 UV-VIS Spectra for 0.2 Micrometers of Carbon
             on Polycarbonate

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SAMPLE	COATING THICKNESS (Micrometers)	% REFLECTION		
		BLUE	GREEN	AMBER
#1, 3440-C-10	0.8	0.62	0.60	0.53
#2, 3440-2-12	0.2	0.68	0.80	0.59
#3, 3440-2-12	None	0.41	0.53	0.40

FIGURE 5.4.3 Reflectance Spectra Mode on Carbon Coated Polycarbonate with the Preliminary System

SAMPLE NUMBER	COATING	EXPOSURE	TRANSMISSION (%) AT:		
			420nm	520nm	620nm
1	None	As Received	82	89	90
2	None	As Received	81	90	91
		AVERAGE	82	90	90
3	0.6μm Carbon	As Coated	76	90	90
4	"	As Coated	74	89	91
5	"	As Coated	75	88	91
6	"	As Coated	74	89	90
		AVERAGE	75	89	90
7	0.6μm Carbon	1 day @ 120°F @95% RH	76	88	89
8	0.6μm Carbon	5 days @ 120°F @ 95% RH	80	91	91
9	0.6μm Carbon	10 days @ 120°F @ 95% RH	77	89	89
10	0.6μm Carbon	20 days @ 120°F @ 95% RH	77	89	90

Table 5.4.4   Optical Transmission Measurements for Improved Coating System for SL-3000 Polycarbonate Sample.

adhesion. After the samples were stabilized to laboratory conditions, a period of about 1 hour, the samples were placed is a UV-VIS spectrophotometer for measurement at wavelengths listed in the previous optical characterization section. The appearance of the samples and their optical values indicated the humidity exposure had no deliterious effect on the transmission or imaging qualities of the coating after aging.

Following the optical characterization, these same samples were placed in an adhesion tester to measure bond strength using the same epoxying technique and methods as used for the as-coated specimens. The results of these tests indicated the bond strengths to be less than 100 psi, which is the minimum value recorded by the bond strength tester. We feel that chemical components in the plastic substrate migrated to the surface under the film and reduced the bond strength.

Another test was exposure to ultraviolet radiation. The prepared test specimens, 2.5 x 2.5 cm , were placed in a UV lamp housing used for erasing semiconductor memory-eproms. This exposed the specimens to a radiation density of approximately miliwatts/cm^2, at a peak wavelength of approximately 290 nm. Samples which were exposed for a period of one day consisted of an uncoated sample as well as two coated specimens. After this period of time, there appeared to be an oily layer form on the surface of the uncoated specimens. Examination by bond strength

testing of the coated specimens again revealed the bond strength was less than 100 psi.

Based on the preceding exposure tests, the thermal cycling and direct high temperature exposure tests were not continued. It appeared that other failure mechanisms were present which were causing the adhesion of the coating to decrease with time. Further investigation of a set of samples which were stored on a sunlight exposed laboratory bench for six months, revealed similar degradation in adhesion between the film and the substrate.

A series of chemical tests were performed in which 2.5 cm squares of the coated samples were exposed to various chemical reagents for various periods. The first chemical exposure test was used to evaluate the effects of three common reagents on the coated substrates:

1) Anti-icing solution: 50% ethylene glycol, 50% water (by weight).

2) MIL-H 5606 hydraulic oil.

3) Fisher Sparkleen detergent solution.

These three solutions were placed in the test fixture shown in Figure 5.5.1. This photograph shows nine 2.5 cm coated polycarbonate specimens each containing an aluminum O-ring sealed well in which the appropriate reagent was placed. Exposure was continued for a period of one week (168 hours) at $23° \pm 2°C$. The

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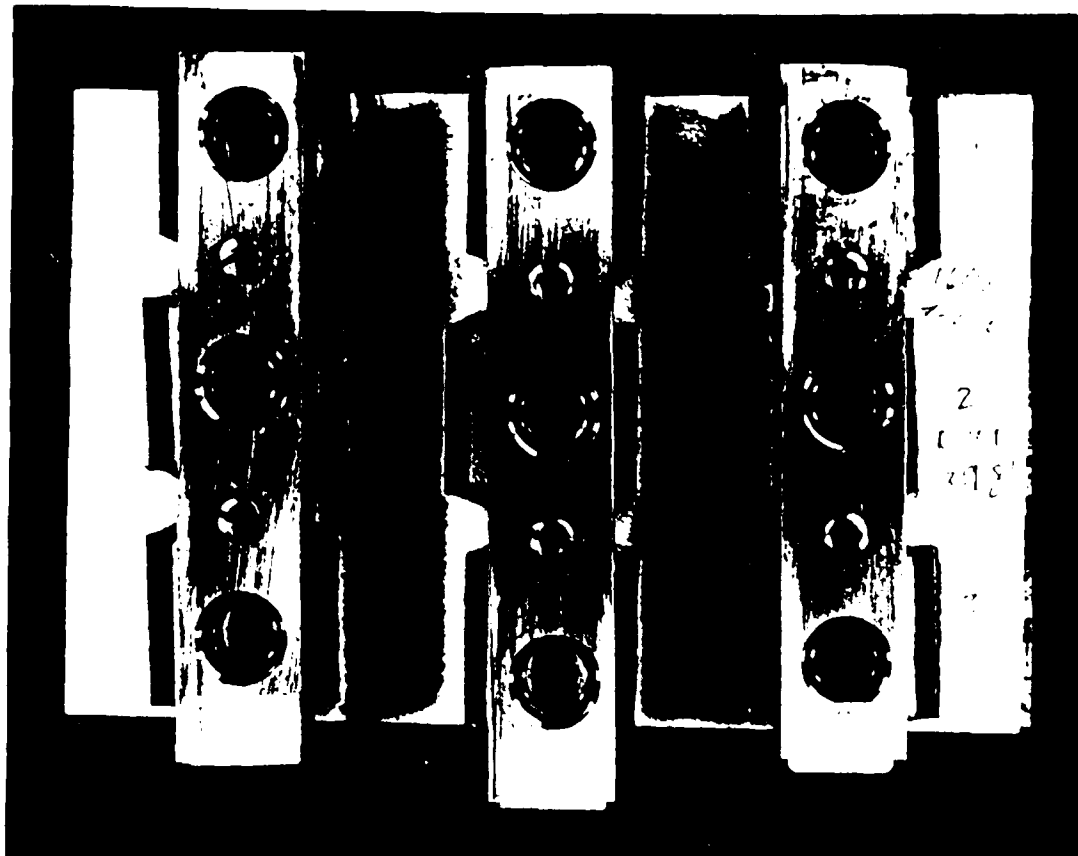
Figure 5.5.1 Chemical Exposure Test Apparatus

results of this exposure test are illustrated in Figure 5.5.2.
The effects of the three reagents on specimens is obvious. The
detergent and anti-icing solutions caused delamination of the
coating from the substrate. The hydraulic oil appeared to have
caused no delamination.

Another potential reagent which may be encountered in use
would be hydrocarbon solvents. A 9 cm x 3 cm coated sample of
polycarbonate was exposed at three spots to methylene chloride for
a period of 5 minutes. This was done at intervals of one minute
and four minutes with observations taken after each period. A
photograph of the tested sample is included in Figure 5.5.3.
After one minute exposure, there was no detectable change in the
surface of the coating or the polycarbonate. After five minutes
exposure, a series of tiny pinholes developed in the surface
showing potential locations where delamination and attack of the
substrate was occurring.

Another test which was felt to be more meaningful regarding
such a severe solvent attack, would be to wipe the coated surface
with a cloth containing acetone. This test was performed on a
disk 8 cm in diameter, one half of which was coated with 0.6
micrometer of ion deposited carbon. The other half was uncoated.
The wipe test produced severe crazing and stressing of the
uncoated side, while the coated side indicated no attack had
occurred. The results of this test are illustrated in Figure
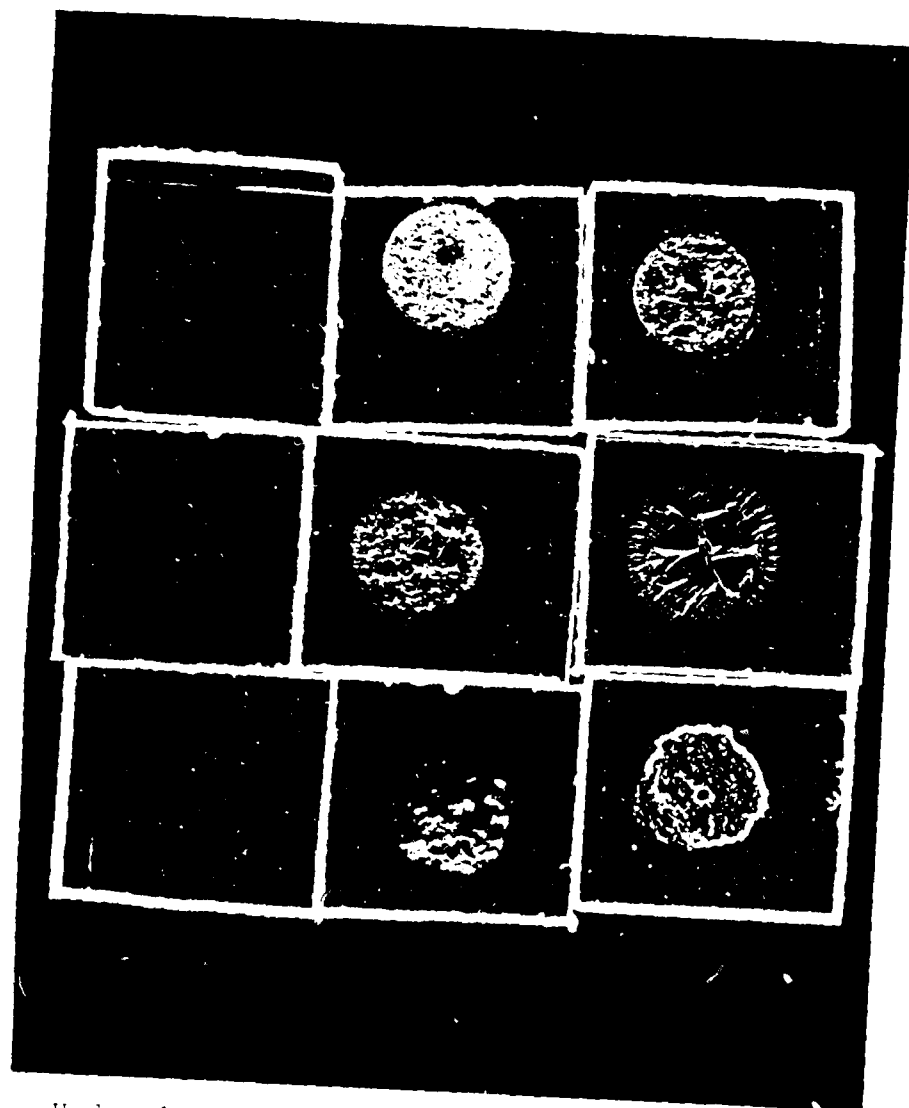
Hydraulic Oil   Anti-Icing   Detergent

Figure 5.5.2 Carbon Coated SL-3000 Test Specimens After
168 Hours at 23°C to Reagents
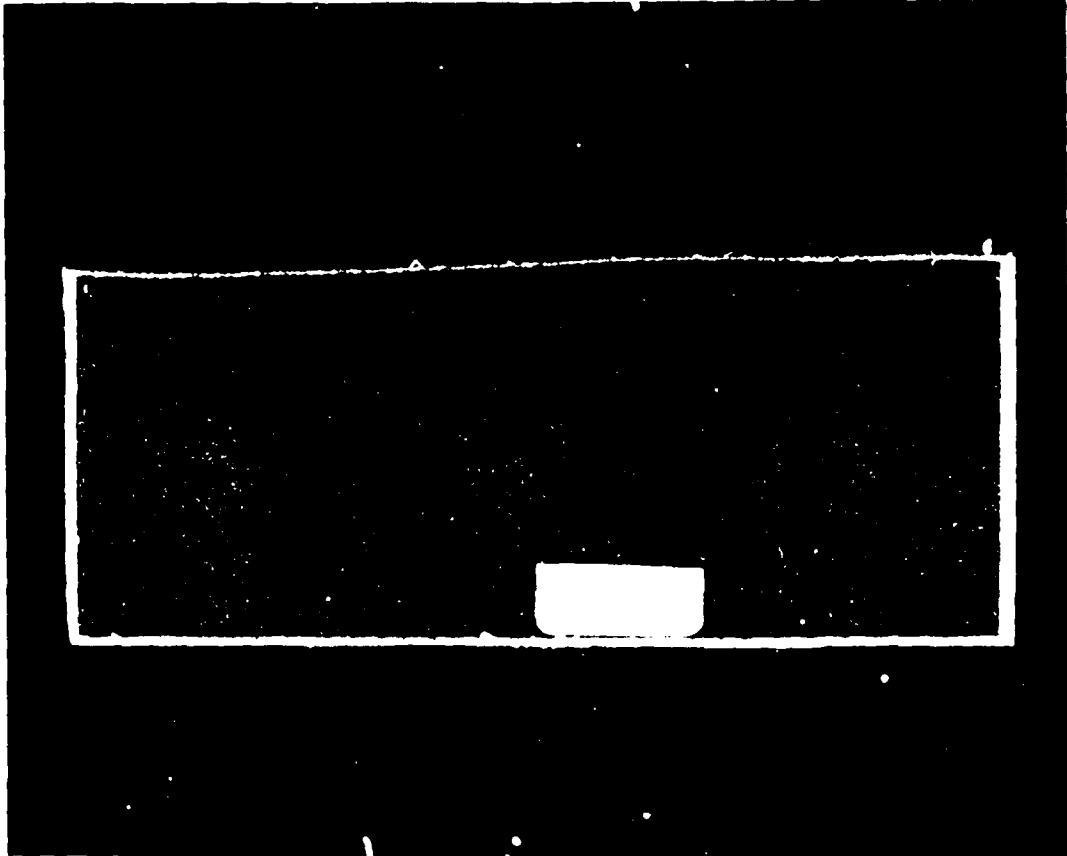
Figure 5.5.3   Carbon Coated Polycarbonate After a Five
              Minute Exposure to Methylene Chloride at
              $23°C$

5.5.4. The specimen was eliminated with a bright central light to produce a glare pattern showing the effect of solvent attack. This type of exposure would probably be more typical in application than would extended immersion.

5.6 Abrasion

A key objective of a protective coating is to enhance the abrasion resistance of the substrate, particularly a relatively soft one such as polycarbonate. To document the relative abrasion resistance of the coating, samples were submitted to the Air Force Wright Aeronautical Laboratories to the attention of Mr. T.J. Reinhart. There the samples were tested for abrasion as outlined on the data sheets given in Tables 5.6.1 and 5.6.2. These tables list the comparative abrasion resistance results for the coated and uncoated specimens respectively. Significant improvement in abrasion resistance afforded by the coating is obvious resulting in reduced haze.

Figure 5.5.4 Partially Carbon Coated Polycarbonate Showing
Protection from Solvent (Acetone) Wipe

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BAYTER ABRASION

MEDIA TYPE   Quartz Silica (6/14)   MEDIA QUANTITY   1 Kg.

ACCOUNT NO. 93507-15   CYCLES/MIN. 150 (300 strokes)

2"   From: Applied Science Laboratories

| SAMPLE | CYCLES | % TRANSMITTED | | % OF HAZE |
		Diffuse	Luminous	
62	0	23	849	3.30
	50	125	814	15.36
	100	68	831	8.18
	150	87	828	10.51
	300	121	818	14.79
63	0	26	834	3.12
	50	66	828	7.97
	100	92	825	11.15
	150	97	826	11.74
	300	174	818	21.27
64	0	20	840	2.38
	50	110	831	13.24
	100	102	839	12.16
	150	133	835	15.93
	300	214	822	26.03
65	0	25	848	2.95
	50	63	839	7.51
	100	95	834	11.39
	150	133	826	16.10
	300	224	817	27.42

AVERAGE PERCENTAGE OF HAZE		
0	--	2.94
50	--	11.02
100	--	10.72
150	--	13.57
300	--	22.38

Figure 5.6.1   Abrasion Results for Carbon Coated Samples and
Polycarbonate

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BAYTER ABRASION

MEDIA TYPE Quartz Silica (6/14)   MEDIA QUANTITY 1 Kg.

ACCOUNT NO. 93507-15   CYCLES/MIN. 150 (300 strokes)

4" Uncoated Standards   Applied Science Laboratories

| SAMPLE | CYCLES | % TRANSMITTED | | % of HAZE |
		Diffuse	Luminous	
S1	0	3	829	.40
	50	114	798	14.29
	100	314	785	40.00
	150	282	777	49.29
	300	470	759	61.92
S2	0	4	831	.50
	50	203	804	25.25
	100	300	795	37.74
	150	358	792	45.20
	300	457	780	58.59
S3	0	5	833	.60
	50	205	798	25.69
	100	275	789	34.85
	150	338	783	43.17
	300	430	783	54.92
S4	0	7	826	.85
	50	220	775	28.39
	100	310	792	39.14
	150	382	776	49.23
	300	457	763	59.90
S5	0	6	810	.74
	50	214	799	26.78
	100	299	773	38.68
	150	368	769	47.85
	300	455	752	60.51

AVERAGE PERCENT OF HAZE

0	--	.62
50	--	24.08
100	--	38.08
150	--	46.95
300	--	59.17

Figure 5.6.2 Abrasion Results for Uncoated Polycarbonate

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6.0   DISCUSSION OF RESULTS

In the previous sections, we have seen that ion deposited
carbon films less than 1 micron thick can be successfully
deposited on polycarbonate substrates. Furthermore, this process
is scalable and amenable to a production type system. Some regard
however, must be given to degradation mechanisms and other pro ess
factors which could influence adhesion as well as uniformity.

The observations made above indicated that the composition
and thickness of the film can be controlled within acceptable
limits (10%) for most visible applications. The thickness of the
coating can be varied depending upon the time the substrate is in
the coater. Thickness on the order of 0.6 micrometers, as used in
this program, appear to give initially satisfactory results.

The adhesion of the coating to the substrate appears to be
very good for a period of at least several weeks after deposition.
However, on coatings which had been evaluated over six months
after coating, the adhesion dropped significantly although
spontaneous delamination or wiping off of the coating was not
observed. Furthermore, the adhesion of the coating was affected
by the surface active agents including the detergent tested and
ethylene glycol.

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There are several possible causes of the delamination and adhesion problems observed. In some of the chemical tests, microscopic pinholes were observed as breaks in the film surface. This may have been due to dust or contamination prior to or during the coating process or may actually be cracks in the coating. Further work would be required to evaluate the exact nature of these locations and should be given serious consideration with respect to the abrasion resistant and solvent resistant aspects of these coatings. A thinner coating than 0.6 microns (6000A) is suggested in order to reduce the chance of cracking.

Degradation of bond strength wil time indicates that surface preparation and coating techniques were suitable to permit good adhesion. Based on the observed degradation following UV exposure, the top polymer surface produced byproducts which could not maintain adhesion. These byproducts appeared as an oily film on exposed uncoated substrates and could be out diffusion of plastic additives. It is also a possibility that the energetic ion deposition process may have initiated the degradation mechanisms. Various surface analysis techniques could be used to analyze the failed portions of the substrate to determine the byproducts produced where the bond failure actually occurred. This would allow understanding of the degradation mechanism and could produce methods for improving the deposition processes.

We feel that slow out diffusion of the additive in the plastic substrate could be the cause of the slow loss of bond strength. There are potential solutions to this problem.

7.0 DELIVERABLES

Under this program two scheduled submissions were made of
test specimens cut to the shapes and provided in the quantity as
requested in a letter dated 28 December 79 from E.A. Arvay. The
first submission was shipped 15 January 80. This series of
coatings was made with the preliminary system. The second
shipment was made.

CARBON COATED TEST SPECIMENS

TYPE OF TEST PERFORMED	# OF RUNS	RUN Nos. 3440-	SUBSTRATE INFORMATION
ABRASION	4	62,63,64,65	Specimens on 2" x 2" substrate coating centered.
FLEXURAL	3	66,67	2 Specimens on 1" x 7" substrate coating midway between ends.
		68	1 Specimen on 1" x 7" substrate coating 2-3/8 $\pm$ ¼" from end.
EROSION	5	69,70,71	3 Specimens on 1" x 1" substrate.
		72,73	2 Specimens on 2" x 2" substrate coating centered.
OPTICAL	3	74,75,76	3 Specimens on 2" x 2" substrate coating centered.
DISPLAY	1	77	1 Specimen on 3" x 3" substrate coating centered.

Table 7.1   Carbon Coated Test Specimens Submitted to Sponsor 1/15/80 from Preliminary System

8.0   ENVIRONMENTAL CONSEQUENCES

The ion coating technology from the standpoint of the product itself and the potential for future scale up appears to have no adverse or potentially adverse environmental consequences. There are no identifiable water or air pollution by-products generated by the process. Nor have any of the products been assessed as having any adverse effects.

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APPENDIX A

Conversion Chart for SI Units

THE INTERNATIONAL SYSTEM OF UNITS

PHYSICAL CONSTANTS and CONVERSION FACTORS
SECOND REVISION

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University of Illinois

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FOREWORD

The International System of Units, Système International d'Unités (designated SI in all languages), is the system of units of measurement which has been adopted by 41 of the principal industrial nations of the world which are signatories to the Convention of the Meter. The 11th, 12th, 13th, and 14th General Conferences on Weights and Measures (meeting in October of 1960, 1964, 1967, and 1971, respectively) have brought the International System of Units to a state of completeness and coherence which make it increasingly more attractive for all applications.

The National Bureau of Standards of the United States announced in Administrative Bulletin 64-6 dated February 1964 that—

> Henceforth it shall be the policy of the National Bureau of Standards to use the units of the International System (SI), as adopted by the Eleventh General Conference on Weights and Measures . . . , except when the use of these units would obviously impair communication or reduce the usefulness of a report to the primary recipients.

A similar position was enunciated by the National Aeronautics and Space Administration in NASA Policy Directive NPD 2220.4 dated September 14, 1970—

> Measurement values employed in NASA Technical Reports, Technical Notes, Technical Memoranda, Contractor Reports, and Special Publications shall be expressed in the International System of Units (SI).

However, the Official-in-Charge of a NASA Headquarters Office or the Director of a NASA Field Installation retains the authority to waive the provisions of NPD 2220.4 in special cases.

This document, NASA SP-7012, gives the names, symbols, and definitions of SI units, the values of physical constants expressed in SI units, and tables of numerical factors for converting miscellaneous units to SI units. It was first published in October 1964. A revised edition was published in 1969 to include resolutions agreed to by members of the 12th and 13th General Conferences, and new values of physical constants derived by Taylor, Parker, and Langenberg. The present edition incorporates material from the records of the 14th General Conference of 1971, but retains the 1969 values of physical constants. SP-7012 was originally compiled by Dr. E. A. Mechtly when he was employed as a physicist at the Marshall Space Flight Center. He is now an associate professor of electrical engineering at the University of Illinois in Urbana.

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HISTORY OF THE INTERNATIONAL SYSTEM OF UNITS

The International System of Units evolved from the unit of length, the meter, and the unit of mass, the kilogram, which were created by members of the Paris Academy of Sciences, and adopted by the National Assembly of France in 1795. The meter, the kilogram, and several other units came to be known as the metric system of units.

The U.S. Congress legalized the use of the metric system throughout the United States on July 28, 1866. The Act of 1866 reads, in part,

It shall be lawful throughout the United States of America to employ the weights and measures of the metric system; and no contract or dealing, or pleading in any court, shall be deemed invalid or liable to objection because the weights or measures expressed or referred to therein are weights or measures of the metric system.

Effective on April 5, 1893, and subsequently, all legal units of measure used in the United States have been metric units or are defined as exact numerical multiples of metric units. The action establishing metric units as the ultimate base of all U.S. Customary Units is known as the "Mendenhall Order." T. C. Mendenhall was U.S. Superintendent of Standard Weights and Measures in 1893.

A highly significant step in the establishment of internationally uniform standard units of measurement was the signing of the Convention of the Meter by the United States and sixteen other nations on May 20, 1875.

The Convention of the Meter provides for an International Bureau of Weights and Measures on neutral ground at Sèvres, near Paris, France; for an International Committee on Weights and Measures; and for an international General Conference on Weights and Measures. The function of these organs is to devise, refine, and maintain precise internationally uniform standards of measure. The Committee, and Conference voting members, are leading professional metrologists (men who have made the science of measurement their careers) and in many cases are the directors of national bureaus of standards. The Director of the U.S. National Bureau of Standards is a member of both the Committee and the General Conference.

The Eleventh General Conference on Weights and Measures convened in Paris during October 1960, with Dr. A. V. Astin representing the United States. At the Eleventh General Conference, the metric system of units (based on the meter, kilogram, second, ampere, kelvin, and candela) was given the name "International System of Units," and the abbreviation "SI" in all languages.

The Twelfth General Conference convened in Paris during October 1964. Among other actions, the Twelfth Conference redefined the word "liter" as a special name for the cubic decimeter, and authorized temporary use of the "atomic second," but did not abrogate the definition of the second, which is based on the ephemeris of the Earth.

The Thirteenth Conference, meeting in October 1967, did abrogate the ephemeris definition of the second, and replaced it with the atomic definition. Among the other actions of the Thirteenth Conference were a revision of the definition of the candela, a redesignation of the unit of thermodynamic temperature, the kelvin (K), and the addition of six derived units to the international system.

The Fourteenth General Conference, meeting in October 1971, adopted the mole, symbol mol, as an SI base unit, adopted the name pascal, symbol Pa, for N/m^2, and adopted the name siemens, symbol S, for Ω^{-1} among other actions. At the time of the Fourteenth Conference, 41 nations were signatory to the Convention of the Meter.

The Fifteenth General Conference is scheduled for 1975, a century after the initial signing of the Convention of the Meter.

The International System of Units is recommended by members of the General Conference on Weights and Measures for all scientific, technical, practical, and teaching purposes.

On the following pages are the names, symbols, and definitions of SI units, the values of physical constants expressed in SI units, and numerical factors for converting miscellaneous units to SI units.

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NAMES AND SYMBOLS OF SI UNITS

Quantity	Name of Unit	Symbol	
	SI BASE UNITS		
length	meter	m	
mass	kilogram	kg	
time	second	s	
electric current	ampere	A	
thermodynamic temperature	kelvin	K	
luminous intensity	candela	cd	
amount of substance	mole	mol	
	SI DERIVED UNITS		
area	square meter	m^2	
volume	cubic meter	m^3	
frequency	hertz	Hz	s^{-1}
mass density (density)	kilogram per cubic meter	kg/m^3	
speed, velocity	meter per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	meter per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	pascal	Pa	N/m^2
kinematic viscosity	square meter per second	m^2/s	
dynamic viscosity	newton-second per square meter	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity	coulomb	C	$A \cdot s$
potential difference, electromotive force	volt	V	W/A
electric field strength	volt per meter	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per meter	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square meter	cd/m^2	
illuminance	lux	lx	lm/m^2
wave number	1 per meter	m^{-1}	
entropy	joule per kelvin	J/K	
specific heat capacity	joule per kilogram kelvin	$J/(kg \cdot K)$	
thermal conductivity	watt per meter kelvin	$W/(m \cdot K)$	
radiant intensity	watt per steradian	W/sr	
activity (of a radioactive source)	1 per second	s^{-1}	
	SI SUPPLEMENTARY UNITS		
plane angle	radian	rad	
solid angle	steradian	sr	

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DEFINITIONS OF SI UNITS

meter (m)

The *meter* is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2 p_{10}$ and $5 d_5$ of the krypton-86 atom.

mètre (m)

Le *mètre* est la longueur égale à 1 650 763,73 longueurs d'onde dans le vide de la radiation correspondant à la transition entre les niveaux $2 p_{10}$ et $5 d_5$ de l'atome krypton 86.

kilogram (kg)

The *kilogram* is the unit of mass; it is equal to the mass of the international prototype of the kilogram. (The international prototype of the kilogram is a particular cylinder of platinum-iridium alloy which is preserved in a vault at Sèvres, France, by the International Bureau of Weights and Measures.)

kilogramme (kg)

Le *kilogramme* est l'unité de masse; il est égal à la masse du prototype international du kilogramme.

second (s)

The *second* is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

seconde (s)

La *seconde* est la durée de 9 192 631 770 périodes de la radiation correspondant à la transition entre les deux niveaux hyperfins de l'état fondamental de l'atome de césium 133

ampere (A)

The *ampere* is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

ampère (A)

L'*ampère* est l'intensité d'un courant constant qui, maintenu dans deux conducteurs parallèles, rectilignes, de longueur infinie, de section circulaire négligeable et placés à une distance de 1 mètre l'un de l'autre dans le vide, produirait entre ces conducteurs une force égale à 2×10^{-7} newton par mètre de longueur.

kelvin (K)

The *kelvin*, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

kelvin (K)

Le *kelvin*, unité de température thermodynamique, est la fraction 1/273,16 de la température thermodynamique du point triple de l'eau.

candela (cd)

The *candela* is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter.

candela (cd)

La *candela* est l'intensité lumineuse, dans la direction perpendiculaire, d'une surface de 1/600 000 mètre carré d'un corps noir à la température de congélation du platine sous la pression de 101 325 newtons par mètre carré.

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mole (mol)

The *mole* is the amount of substance of a system which contains as many elementary entities as there are carbon atoms in 0.012 kg of carbon 12. The elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

newton (N)

The *newton* is that force which gives to a mass of 1 kilogram an acceleration of 1 meter per second per second

joule (J)

The *joule* is the work done when the point of application of 1 newton is displaced a distance of 1 meter in the direction of the force.

watt (W)

The *watt* is the power which gives rise to the production of energy at the rate of 1 joule per second

volt (V)

The *volt* is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

ohm (Ω)

The *ohm* is the electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.

coulomb (C)

The *coulomb* is the quantity of electricity transported in 1 second by a current of 1 ampere.

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farad (F)

The *farad* is the capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

henry (H)

The *henry* is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.

weber (Wb)

The *weber* is the magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second

lumen (lm)

The *lumen* is the luminous flux emitted in a solid angle of 1 steradian by a uniform point source having an intensity of 1 candela.

radian (rad)

The *radian* is the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius.

steradian (sr)

The *steradian* is the solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

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SI PREFIXES

The names of multiples and submultiples of SI units may be formed by application of the prefixes:

Factor by which unit is multiplied	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

The International Organization for Standardization (ISO) recommends the following rules for the use of SI prefixes:

a) Prefix symbols are printed in roman (upright) type without spacing between the prefix symbol and the unit symbol.

b) An exponent affixed to a symbol containing a prefix indicates that the multiple or sub-multiple of the unit is raised to the power expressed by the exponent,

for example: $1\ cm^{3} = 10^{-6}\ m^{3}$
$1\ cm^{-1} = 10^{2}\ m^{-1}$

c) Compound prefixes, formed by the juxtaposition of two or more SI prefixes, are not to be used.

for example: 1 nm   *but not:* 1 mμm

The International Organization for Standardization (ISO) has issued additional recommendatio is with the aim of securing uniformity in the use of units.

According to these recommendations:

a) The product of two or more units is preferably indicated by a dot. The dot may be dispensed with when there is no risk of confusion with another unit symbol

for example: N·m or N m   *but not:* mN

b) A solidus (oblique stroke, /), a horizontal line, or negative powers may be used to express a derived unit formed from two others by division

for example: m/s, $\dfrac{m}{s}$ or m·s^{-1}

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c) The solidus must not be repeated on the same line unless ambiguity is avoided by parentheses. In complicated cases negative powers or parentheses should be used

for example: m/s²   or   m·s⁻²   *but not:* m/s/s

m·kg/(s³·A) or m·kg·s⁻³·A⁻¹   *but not:* m·kg/s³/A

UNITS OUTSIDE THE INTERNATIONAL SYSTEM

The International Committee on Weights and Measures recognized in 1969 that users of SI units will also wish to employ certain other units which, although they are not SI units, are in widespread use. These units play such an important part that they must be retained for general use with the International System of Units. They are the following:

UNITS IN USE WITH THE INTERNATIONAL SYSTEM

Name	Symbol	Value in SI unit
minute	min	1 min = 60 s
hour	h	1 h = 60 min = 3 600 s
day	d	1 d = 24 h = 86 400 s
degree	°	1° = (π/180) rad
minute	'	1' = (1/60)° = (π/10 800) rad
second	''	1'' = (1/60)' = (π/648 000) rad
liter	l	1 l = 1 dm³ = 10^{-3} m³
tonne	t	1 t = 10^3 kg

It is likewise necessary to recognize, outside the International System, some other units which are useful in specialized fields of scientific research, because their values expressed in SI units must be obtained by experiment, and are therefore not known exactly. They are the following:

UNITS USED WITH THE INTERNATIONAL SYSTEM WHOSE VALUES IN SI UNITS ARE OBTAINED EXPERIMENTALLY

Name	Symbol	Definition
electronvolt	eV	(ᵃ)
unified atomic mass unit	u	(ᵇ)
astronomical unit	(c)	(ᶜ)
parsec	pc	(ᵈ)

(ᵃ) 1 electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of 1 volt in vacuum.

(ᵇ) The unified atomic mass unit is equal to the fraction 1/12 of the mass of an atom of the nuclide ¹²C.

(ᶜ) The astronomical unit does not have an international symbol; abbreviations are used, for example, AU in English, UA in French, AE in German, a.e.д in Russian, etc. The astronomical unit of distance is the length of the radius of the unperturbed circular orbit of a body of negligible mass moving around the Sun with a sidereal angular velocity of 0.017 202 098 950 radian per day of 86 400 ephemeris seconds. In the system of astronomical constants of the International Astronomical Union the value adopted for it is: 1 AU = 149 600 × 10^6 m.

(ᵈ) 1 parsec is the distance at which 1 astronomical unit subtends an angle of 1 second of arc.

In 1969, the International Committee on Weights and Measures listed three additional classes of non-SI units: (1) 12 units which may be used for a limited time, (2) 9 units preferably not used, and (3) 11 units to be avoided. These deprecated units and preferred SI units are discussed in *The International System of Units (SI)*, NBS Special Publication 330. Another useful guide is the *Metric Practice Guide*, ASTM publ. no. E380-72.

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PHYSICAL CONSTANTS

The following lists of physical constants are from the work of B. N. Taylor, W. H. Parker, and D. N. Langenberg (*Reviews of Modern Physics*, July 1969). Their least-squares adjustment of values of the constants depends strongly on a highly accurate (2.4 ppm) determination of e/h from the ac Josephson effect in superconductors, and is believed to be more accurate than the 1963 adjustment which appears to suffer from the use of an incorrect value of the fine structure constant as an input datum. See also NBS Special Publication 344 issued March 1971.

Quantity	Symbol	Value	Error ppm	Prefix	Unit
Speed of light in vacuum	c	2. 997 925 0	0. 33	$\times 10^{8}$	m s^{-1}
Gravitational constant	G	6. 673 2	460	10^{-11}	N m^2 kg^{-2}
Avogadro constant	N_A	6. 022 169	6. 6	10^{26}	kmol^{-1}
Boltzmann constant	k	1. 380 622	43	10^{-23}	J K^{-1}
Gas constant	R	8. 314 34	42	10^{3}	J kmol^{-1} K^{-1}
Volume of ideal gas, standard conditions	V_0	2. 241 36	....	10^{1}	m^3 kmol^{-1}
Faraday constant	F	9. 648 670	5. 5	10^{7}	C kmol^{-1}
Unified atomic mass unit	u	1. 660 531	6. 6	10^{-27}	kg
Planck constant	h	6. 626 196	7. 6	10^{-34}	J s
	$h/2\pi$	1. 054 591 9	7. 6	10^{-34}	J s
Electron charge	e	1. 602 191 7	4. 4	10^{-19}	C
Electron rest mass	m_e	9. 109 558	6. 0	10^{-31}	kg
		5. 485 930	6. 2	10^{-4}	u
Proton rest mass	m_p	1. 672 614	6. 6	10^{-27}	kg
		1. 007 276 61	0. 08	....	u
Neutron rest mass	m_n	1. 674 920	6. 6	10^{-27}	kg
		1. 008 665 20	0. 10	....	u
Electron charge to mass ratio	e/m_e	1. 758 802 8	3. 1	10^{11}	C kg^{-1}
Stefan-Boltzmann constant	σ	5. 669 61	170	10^{-8}	W m^{-2} K^{-4}
First radiation constant	$2\pi hc^2$	3. 741 844	7. 6	10^{-16}	W m^2
Second radiation constant	hc/k	1. 438 833	43	10^{-2}	m K
Rydberg constant	R_∞	1. 097 373 12	0. 10	10^{7}	m^{-1}
Fine structure constant	α	7. 297 351	1. 5	10^{-3}	
	α^{-1}	1. 370 360 2	1. 5	10^{+2}	
Bohr radius	a_0	5. 291 771 5	1. 5	10^{-11}	m
Classical electron radius	r_e	2. 817 939	4. 6	10^{-15}	m
Compton wavelength of electron	λ_C	2. 426 309 6	3. 1	10^{-12}	m
	$\lambda_C/2\pi$	3. 861 592	3. 1	10^{-13}	m
Compton wavelength of proton	$\lambda_{C,p}$	1. 321 440 9	6. 8	10^{-15}	m
	$\lambda_{C,p}/2\pi$	2. 103 139	6. 8	10^{-16}	m
Compton wavelength of neutron	$\lambda_{C,n}$	1. 319 621 7	6. 8	10^{-15}	m
	$\lambda_{C,n}/2\pi$	2. 100 243	6. 8	10^{-16}	m
Electron magnetic moment	μ_e	9. 284 851	7. 0	10^{-24}	J T^{-1}
Proton magnetic moment	μ_p	1. 410 620 3	7. 0	10^{-26}	J T^{-1}
Bohr magneton	μ_B	9. .274 096	7. 0	10^{-24}	J T^{-1}
Nuclear magneton	μ_n	5. 050 951	10	10^{-27}	J T^{-1}
Gyromagnetic ratio of protons in H$_2$O	γ'_p	2. 675 127 0	3. 1	10^{8}	rad s^{-1} T^{-1}
	$\gamma'_p/2\pi$	4. 257 597	3. 1	10^{7}	Hz T^{-1}
Gyromagnetic ratio of protons in H$_2$O corrected for diamagnetism of H$_2$O.	γ_p	2. 675 196 5	3. 1	10^{8}	rad s^{-1} T^{-1}
	$\gamma_p/2\pi$	4. 257 707	3. 1	10^{7}	Hz T^{-1}
Magnetic flux quantum	ϕ_0	2. 067 853 8	3. 3	10^{-15}	Wb
Quantum of circulation	$h/2m_e$	3. 636 947	3. 1	10^{-4}	J s kg^{-1}
	h/m_e	7. 273 894	3. 1	10^{-4}	J s kg^{-1}

Unitless numerical ratios	Value	Error ppm	Prefix
(c^2) kg/eV	5. 609 538	4. 4	10^{35}
(c^2) u/eV	9. 314 812	5. 5	10^{8}
u/kg	1. 660 531	6. 6	10^{-27}
(c^2) m_e/eV	5. 110 041	3. 1	10^{5}
(c^2) m_p/eV	9. 382 592	5. 5	10^{8}
(c^2) m_n/eV	9. 395 527	5. 5	10^{8}
eV/J	1. 602 191 7	4. 4	10^{-19}
(h^{-1}) eV/Hz	2. 417 965 9	3. 3	10^{14}
$(hc)^{-1}$ eV m	8. 065 465	3. 3	10^{5}
(k^{-1}) eV/K	1. 160 485	42	10^{4}
(hc) (eV m)$^{-1}$	1. 239 854 1	3. 3	10^{-6}
(hc) R_∞/J	2. 179 914	7. 6	10^{-18}
(hc) R_∞/eV	1. 360 582 6	3. 3	10^{1}
(c) R_∞/Hz	3. 289 842 3	0. 35	10^{15}
(hc/k) R_∞/K	1. 578 936	43	10^{5}
m_p/m_e	1. 836 109	6. 2	10^{3}
μ_e/μ_B	1. 001 159 638 9	0. 0031	
μ'_p/μ_B	1. 520 993 12	0. 066	10^{-3}
μ_p/μ_B	1. 521 032 64	0. 30	10^{-3}
μ'_p/μ_n	2. 792 709	6. 2	
μ_p/μ_n	2. 792 782	6. 2	

Other important constants

$\pi = 3.141\ 592\ 653\ 589$

$e = 2.718\ 281\ 828\ 459$

$\mu_0 = 4\pi \times 10^{-7}$ H/m (exact), permeability of free space
$= 1.256\ 637\ 061 \times 10^{-6}$ H/m

$\epsilon_0 = \mu_0^{-1} c^{-2}$ F/m, permittivity of free space
$= 8.854\ 185 \times 10^{-12}$ F/m

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CONVERSION FACTORS

The following tables express the definitions of miscellaneous units of measure as exact numerical multiples of coherent SI units, and provide multiplying factors for converting numbers and miscellaneous units to corresponding new numbers and SI units.

The first two digits of each numerical entry represent a power of 10. An asterisk follows each number which expresses an exact definition. For example, the entry "−02 2.54*" expresses the fact that 1 inch=2.54×10⁻² meter, exactly, by definition. Most of the definitions are extracted from National Bureau of Standards documents. Numbers not followed by an asterisk are only approximate representations of definitions, or are the results of physical measurements.

The conversion factors are listed alphabetically and by physical quantity.

The Listing by Physical Quantity includes only relationships which are frequently encountered and deliberately omits the great multiplicity of combinations of units which are used for more specialized purposes. Conversion factors for combinations of units are easily generated from numbers given in the Alphabetical Listing by the technique of direct substitution or by other well-known rules for manipulating units. These rules are adequately discussed in many science and engineering textbooks and are not repeated here.

ALPHABETICAL LISTING

To convert from	to	multiply by
abampere	ampere	+01 1.00*
abcoulomb	coulomb	+01 1.00*
abfarad	farad	+09 1.00*
abhenry	henry	−09 1.00*
abmho	siemens	+09 1.00*
abohm	ohm	−09 1.00*
abvolt	volt	−08 1.00*
acre	meter²	+03 4.046 856 422 4*
angstrom	meter	−10 1.00*
are	meter²	+02 1.00*
astronomical unit (IAU)	meter	+11 1.496 00
astronomical unit (radio)	meter	+11 1.495 978 9
atmosphere	newton/meter²	+05 1.013 25*
bar	newton/meter²	+05 1.00*
barn	meter²	−28 1.00*
barrel (petroleum, 42 gallons)	meter³	−01 1.589 873
barye	newton/meter²	−01 1.00*
board foot (1'×1'×1'')	meter³	−03 2.359 737 216*
British thermal unit:		
(IST before 1956)	joule	+03 1.055 04
(IST after 1956)	joule	+03 1.055 056
British thermal unit (mean)	joule	+03 1.055 87
British thermal unit (thermochemical)	joule	+03 1.054 350
British thermal unit (39° F)	joule	+03 1.059 67
British thermal unit (60° F)	joule	+03 1.054 68
bushel (U.S.)	meter³	−02 3.523 907 016 688*
cable	meter	+02 2.194 56*
caliber	meter	−04 2.54*
calorie (International Steam Table)	joule	+00 4.1868
calorie (mean)	joule	+00 4.190 02
calorie (thermochemical)	joule	+00 4.184*
calorie (15° C)	joule	+00 4.185 80

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To convert from	to	multiply by
calorie (20° C)	joule	+00 4.181 90
calorie (kilogram, International Steam Table)	joule	+03 4.1868
calorie (kilogram, mean)	joule	+03 4.190 02
calorie (kilogram, thermochemical)	joule	+03 4.184*
carat (metric)	kilogram	−04 2.00*
Celsius (temperature)	kelvin	$t_K = t_C + 273.15$
centimeter of mercury (0° C)	newton/meter²	+03 1.333 22
centimeter of water (4° C)	newton/meter²	+01 9.806 38
chain (engineer or ramden)	meter	+01 3.048*
chain (surveyor or gunter)	meter	+01 2.011 68*
circular mil	meter²	−10 5.067 074 8
cord	meter³	+00 3.624 556 3
cubit	meter	−01 4.572*
cup	meter⁴	−04 2.365 882 365*
curie	disintegration/second	+10 3.70*
day (mean solar)	second (mean solar)	+04 8.64*
day (sidereal)	second (mean solar)	+04 8.616 409 0
degree (angle)	radian	−02 1.745 329 251 994 3
denier (international)	kilogram/meter	−07 1.00*
dram (avoirdupois)	kilogram	−03 1.771 845 195 312 5*
dram (troy or apothecary)	kilogram	−03 3.887 934 6*
dram (U.S. fluid)	meter³	−06 3.696 691 195 312 5*
dyne	newton	−05 1.00*
electron volt	joule	−19 1.602 191 7
erg	joule	−07 1.00*
Fahrenheit (temperature)	kelvin	$t_K = (5/9)(t_F + 459.67)$
Fahrenheit (temperature)	Celsius	$t_C = (5/9)(t_F - 32)$
faraday (based on carbon 12)	coulomb	+04 9.648 70
faraday (chemical)	coulomb	+04 9.649 57
faraday (physical)	coulomb	+04 9.652 19
fathom	meter	+00 1.828 8*
fermi (femtometer)	meter	−15 1.00*
fluid ounce (U.S.)	meter³	−05 2.957 352 956 25*
foot	meter	−01 3.048*
foot (U.S. survey)	meter	+00 1200/3937*
foot (U.S. survey)	meter	−01 3.048 006 096
foot of water (39.2° F)	newton/meter²	+03 2.988 98
footcandle	lumen/meter²	+01 1.076 391 0
footlambert	candela/meter²	+00 3.426 259
free fall, standard	meter/second²	+00 9.806 65*
furlong	meter	+02 2.011 68*
gal (galileo)	meter/second²	−02 1.00*
gallon (U.K. liquid)	meter³	−03 4.546 087
gallon (U.S. dry)	meter³	−03 4.404 883 770 86*
gallon (U.S. liquid)	meter³	−03 3.785 411 784*
gamma	tesla	−09 1.00*
gauss	tesla	−04 1.00*
gilbert	ampere turn	−01 7.957 747 2
gill (U.K.)	meter³	−04 1.420 652
gill (U.S.)	meter³	−04 1.182 941 2
grad	degree (angular)	−01 9.00*
grad	radian	−02 1.570 796 3
grain	kilogram	−05 6.479 891*
gram	kilogram	−03 1.00*

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To convert from	to	multiply by
hand	meter	−01 1.016*
hectare	meter²	+04 1.00*
hogshead (U.S.)	meter³	−01 2.384 809 423 92*
horsepower (550 foot lbf/second)	watt	+02 7.456 998 7
horsepower (boiler)	watt	+03 9.809 50
horsepower (electric)	watt	+02 7.46*
horsepower (metric)	watt	+02 7.354 99
horsepower (U.K.)	watt	+02 7.457
horsepower (water)	watt	+02 7.460 43
hour (mean solar)	second (mean solar)	+03 3.60*
hour (sidereal)	second (mean solar)	+03 3.590 170 4
hundredweight (long)	kilogram	+01 5.080 234 544*
hundredweight (short)	kilogram	+01 4.535 923 7*
inch	meter	−02 2.54*
inch of mercury (32° F)	newton/meter²	+03 3.386 389
inch of mercury (60° F)	newton/meter²	+03 3.376 85
inch of water (39.2° F)	newton/meter²	+02 2.490 82
inch of water (60° F)	newton/meter²	+02 2.4884
kayser	1/meter	+02 1.00*
kilocalorie (International Steam Table)	joule	+03 4.186 8
kilocalorie (mean)	joule	+03 4.190 02
kilocalorie (thermochemical)	joule	+03 4.184*
kilogram mass	kilogram	+00 1.00*
kilogram force (kgf)	newton	+00 9.806 65*
kilopound force	newton	+00 9.806 65*
kip	newton	+03 4.448 221 615 260 5*
knot (international)	meter/second	−01 5.144 444 444
lambert	candela/meter²	+04 1/π*
lambert	candela/meter²	+03 3.183 098 8
langley	joule/meter²	+04 4.184*
lbf (pound force, avoirdupois)	newton	+00 4.448 221 615 260 5*
lbm (pound mass, avoirdupois)	kilogram	−01 4.535 923 7*
league (U.K. nautical)	meter	+03 5.559 552*
league (international nautical)	meter	+03 5.556*
league (statute)	meter	+03 4.828 032*
light year	meter	+15 9.460 55
link (engineer or ramden)	meter	−01 3.048*
link (surveyor or gunter)	meter	−01 2.011 68*
liter	meter³	−03 1.00*
lux	lumen/meter²	+00 1.00*
maxwell	weber	−08 1.00*
meter	wavelengths Kr 86	+06 1.650 763 73*
micron	meter	−06 1.00*
mil	meter	−05 2.54*
mile (U.S. statute)	meter	+03 1.609 344*
mile (U.K. nautical)	meter	+03 1.853 184*
mile (international nautical)	meter	+03 1.852*
mile (U.S. nautical)	meter	+03 1.852*
millibar	newton/meter²	+02 1.00*
millimeter of mercury (0° C)	newton/meter²	+02 1.333 224
minute (angle)	radian	−04 2.908 882 086 66
minute (mean solar)	second (mean solar)	+01 6.00*
minute (sidereal)	second (mean solar)	+01 5.983 617 4
month (mean calendar)	second (mean solar)	+06 2.628*

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To convert from	to	multiply by
nautical mile (international)	meter	+03 1.852*
nautical mile (U.S.)	meter	+03 1.852*
nautical mile (U.K.)	meter	+03 1.853 184*
oersted	ampere/meter	+01 7.957 747 2
ounce force (avoirdupois)	newton	−01 2.780 138 5
ounce mass (avoirdupois)	kilogram	−02 2.834 952 312 5*
ounce mass (troy or apothecary)	kilogram	−02 3.110 347 68*
ounce (U.S. fluid)	meter^3	−05 2.957 352 956 25*
pace	meter	−01 7.62*
parsec (IAU)	meter	+16 3.085 7
pascal	newton/meter^2	+00 1.00*
peck (U.S.)	meter^3	−03 8.809 767 541 72*
pennyweight	kilogram	−03 1.555 173 84*
perch	meter	+00 5.0292*
phot	lumen/meter^2	+04 1.00
pica (printers)	meter	−03 4.217 517 6*
pint (U.S. dry)	meter^3	−04 5.506 104 713 575*
pint (U.S. liquid)	meter^3	−04 4.731 764 73*
point (printers)	meter	−04 3.514 598*
poise	newton second/meter^2	−01 1.00*
pole	meter	+00 5.0292*
pound force (lbf avoirdupois)	newton	+00 4.448 221 615 260 5*
pound mass (lbm avoirdupois)	kilogram	−01 4.535 923 7*
pound mass (troy or apothecary)	kilogram	−01 3.732 417 216*
poundal	newton	−01 1.382 549 543 76*
quart (U.S. dry)	meter^3	−03 1.101 220 942 715*
quart (U.S. liquid)	meter^3	−04 9.463 592 5
rad (radiation dose absorbed)	joule/kilogram	−02 1.00*
Rankine (temperature)	kelvin	$t_K = (5/9)t_R$
rayleigh (rate of photon emission)	1/second meter^2	+10 1.00*
rhe	meter^2/newton second	+01 1.00*
rod	meter	+00 5.0292*
roentgen	coulomb/kilogram	−04 2.579 76*
rutherford	disintegration/second	+06 1.00*
second (angle)	radian	−06 4.848 136 811
second (ephemeris)	second	+00 1.000 000 000
second (mean solar)	second (ephemeris)	Consult American Ephemeris and Nautical Almanac
second (sidereal)	second (mean solar)	−01 9.972 695 7
section	meter^2	+06 2.589 988 110 336*
scruple (apothecary)	kilogram	−03 1.295 978 2*
shake	second	−08 1.00
skein	meter	+02 1.097 28*
slug	kilogram	+01 1.459 390 29
span	meter	−01 2.286*
statampere	ampere	−10 3.335 640
statcoulomb	coulomb	−10 3.335 640
statfarad	farad	−12 1.112 650
stathenry	henry	+11 8.987 554
statohm	ohm	+11 8.987 554
statute mile (U.S.)	meter	+03 1.609 344*
statvolt	volt	+02 2.997 925
stere	meter^3	+00 1.00*

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To convert from	to	multiply by
stilb	candela/meter²	+04 1.00
stoke	meter²/second	−04 1.00*
tablespoon	meter³	−05 1.478 676 478 125*
teaspoon	meter³	−06 4.928 921 593 75*
ton (assay)	kilogram	−02 2.916 666 6
ton (long)	kilogram	+03 1.016 046 908 8*
ton (metric)	kilogram	+03 1.00*
ton (nuclear equivalent of TNT)	joule	+09 4.20
ton (register)	meter³	+00 2.831 684 659 2*
ton (short, 2000 pound)	kilogram	+02 9.071 847 4*
tonne	kilogram	+03 1.00*
torr (0° C)	newton/meter²	+02 1.333 22
township	meter³	+07 9.323 957 2
unit pole	weber	−07 1.256 637
yard	meter	−01 9.144*
year (calendar)	second (mean solar)	+07 3.1536*
year (sidereal)	second (mean solar)	+07 3.155 815 0
year (tropical)	second (mean solar)	+07 3.155 692 6
year 1900, tropical, Jan., day 0, hour 12	second (ephemeris)	+07 3.155 692 597 47*
year 1900, tropical, Jan., day 0, hour 12	second	+07 3.155 692 597 47

LISTING BY PHYSICAL QUANTITY

ACCELERATION

foot/second²	meter/second²	−01 3.048*
free fall, standard	meter/second²	+00 9.806 65*
gal (galileo)	meter/second²	−02 1.00*
inch/second²	meter/second²	−02 2.54*

AREA

acre	meter²	+03 4.046 856 422 4*
are	meter²	+02 1.00*
barn	meter²	−28 1.00*
circular mil	meter²	−10 5.067 074 8
foot²	meter²	−02 9.290 304*
hectare	meter²	+04 1.00*
inch²	meter²	−04 6.4516*
mile² (U.S. statute)	meter²	+06 2.589 988 110 336*
section	meter²	+06 2.589 988 110 336*
township	meter²	+07 9.323 957 2
yard²	meter²	−01 8.361 273 6*

DENSITY

gram/centimeter³	kilogram/meter³	+03 1.00*
lbm/inch³	kilogram/meter³	+04 2.767 990 5
lbm/foot³	kilogram/meter³	+01 1.601 846 3
slug/foot³	kilogram/meter³	+02 5.153 79

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ENERGY

British thermal unit:

(IST before 1956)	joule	+03 1.055 04
(IST after 1956)	joule	+03 1.055 056
British thermal unit (mean)	joule	+03 1.055 87
British thermal unit (thermochemical)	joule	+03 1.054 350
British thermal unit (39° F)	joule	+03 1.059 67
British thermal unit (60° F)	joule	+03 1.054 68
calorie (International Steam Table)	joule	+00 4.1868
calorie (mean)	joule	+00 4.190 02
calorie (thermochemical)	joule	+00 4.184*
calorie (15° C)	joule	+00 4.185 80
calorie (20° C)	joule	+00 4.181 90
calorie (kilogram, International Steam Table)	joule	+03 4.1868
calorie (kilogram, mean)	joule	+03 4.190 02
calorie (kilogram, thermochemical)	joule	+03 4.184*
electron volt	joule	−19 1.602 191 7
erg	joule	−07 1.00*
foot lbf	joule	+00 1.355 817 9
foot poundal	joule	−02 4.214 011 0
joule (international of 1948)	joule	+00 1.000 165
kilocalorie (International Steam Table)	joule	+03 4.1868
kilocalorie (mean)	joule	+03 4.190 02
kilocalorie (thermochemical)	joule	+03 4.184*
kilowatt hour	joule	+06 3.60*
kilowatt hour (international of 1948)	joule	+06 3.600 59
ton (nuclear equivalent of TNT)	joule	+09 4.20
watt hour	joule	+03 3.60*

ENERGY/AREA TIME

Btu (thermochemical)/foot² second	watt/meter²	+04 1.134 893 1
Btu (thermochemical)/foot² minute	watt/meter²	+02 1.891 488 5
Btu (thermochemical)/foot² hour	watt/meter²	+00 3.152 480 8
Btu (thermochemical)/inch² second	watt/meter²	+06 1.634 246 2
calorie (thermochemical)/cm² minute	watt/meter²	+02 6.973 333 3
erg/centimeter² second	watt/meter²	−03 1.00*
watt/centimeter²	watt/meter²	+04 1.00*

FORCE

dyne	newton	−05 1.00*
kilogram force (kgf)	newton	+00 9.806 65*
kilopond force	newton	+00 9.806 65*
kip	newton	+03 4.448 221 615 260 5*
lbf (pound force, avoirdupois)	newton	+00 4.448 221 615 260 5*
ounce force (avoirdupois)	newton	−01 2.780 138 5
pound force, lbf (avoirdupois)	newton	+00 4.448 221 615 260 5*
poundal	newton	−01 1.382 549 543 76*

LENGTH

angstrom	meter	−10 1.00*
astronomical unit (IAU)	meter	+11 1.496 00
astronomical unit (radio)	meter	+11 1.495 978 9
cable	meter	+02 2.194 56*

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To convert from	to	multiply by
caliber	meter	−04 2.54*
chain (surveyor or gunter)	meter	+01 2.011 68*
chain (engineer or ramden)	meter	+01 3.048*
cubit	meter	−01 4.572*
fathom	meter	+00 1.8288*
fermi (femtometer)	meter	−15 1.00*
foot	meter	−01 3.048*
foot (U.S. survey)	meter	+00 1200/3937*
foot (U.S. survey)	meter	−01 3.048 006 096
furlong	meter	+02 2.011 68*
hand	meter	−01 1.016*
inch	meter	−02 2.54*
league (U.K. nautical)	meter	+03 5.559 552*
league (international nautical)	meter	+03 5.556*
league (statute)	meter	+03 4.828 032*
light year	meter	+15 9.460 55
link (engineer or ramden)	meter	−01 3.048*
link (surveyor or gunter)	meter	−01 2.011 68*
meter	wavelengths Kr 86	+06 1.650 763 73*
micron	meter	−06 1.00*
mil	meter	−05 2.54*
mile (U.S. statute)	meter	+03 1.609 344*
mile (U.K. nautical)	meter	+03 1.853 184*
mile (international nautical)	meter	+03 1.852*
mile (U.S. nautical)	meter	+03 1.852*
nautical mile (U.K.)	meter	+03 1.853 184*
nautical mile (international)	meter	+03 1.852*
nautical mile (U.S.)	meter	+03 1.852*
pace	meter	−01 7.62*
parsec (IAU)	meter	+16 3.085 7
perch	meter	+00 5.0292*
pica (printers)	meter	−03 4.217 517 6*
point (printers)	meter	−04 3.514 598*
pole	meter	+00 5.0292*
rod	meter	+00 5.0292*
skein	meter	+02 1.097 28*
span	meter	−01 2.286*
statute mile (U.S.)	meter	+03 1.609 344*
yard	meter	−01 9.144*

MASS

carat (metric)	kilogram	−04 2.00*
gram (avoirdupois)	kilogram	−03 1.771 845 195 312 5*
gram (troy or apothecary)	kilogram	−03 3.887 934 6*
grain	kilogram	−05 6.479 891*
gram	kilogram	−03 1.00*
hundredweight (long)	kilogram	+01 5.080 234 544*
hundredweight (short)	kilogram	+01 4.535 923 7*
kgf second² meter (mass)	kilogram	+00 9.806 65*
kilogram mass	kilogram	+00 1.00*
lbm (pound mass, avoirdupois)	kilogram	−01 4.535 923 7*
ounce mass (avoirdupois)	kilogram	−02 2.834 952 312 5*
ounce mass (troy or apothecary)	kilogram	−02 3.110 347 68*
pennyweight	kilogram	−03 1.555 173 84*
pound mass, lbm (avoirdupois)	kilogram	−01 4.535 923 7*

To convert from	to	multiply by
pound mass (troy or apothecary)	kilogram	01 3.732 417 216*
scruple (apothecary)	kilogram	03 1.295 978 2*
slug	kilogram	+01 1.459 390 29
ton (assay)	kilogram	02 2.916 666 6
ton (long)	kilogram	+03 1.016 046 908 8*
ton (metric)	kilogram	+03 1.00*
ton (short, 2000 pound)	kilogram	+02 9.071 847 4*
tonne	kilogram	+03 1.00*

POWER

Btu (thermochemical)/second	watt	+03 1.054 350 264 488
Btu (thermochemical)/minute	watt	+01 1.757 250 4
calorie (thermochemical)/second	watt	+00 4.184*
calorie (thermochemical)/minute	watt	−02 6.973 333 3
foot lbf/hour	watt	−04 3.766 161 0
foot lbf/minute	watt	02 2.259 696 6
foot lbf/second	watt	+00 1.355 817 9
horsepower (550 foot lbf/second)	watt	+02 7.456 998 7
horsepower (boiler)	watt	+03 9.809 50
horsepower (electric)	watt	+02 7.46*
horsepower (metric)	watt	+02 7.354 99
horsepower (U.K.)	watt	+02 7.457
horsepower (water)	watt	+02 7.460 43
kilocalorie (thermochemical)/minute	watt	+01 6.973 333 3
kilocalorie (thermochemical)/second	watt	+03 4.184*
watt (international of 1948)	watt	+00 1.000 165

PRESSURE

atmosphere	newton/meter²	+05 1.013 25*
bar	newton/meter²	+05 1.00*
barye	newton/meter²	−01 1.00*
centimeter of mercury (0° C)	newton/meter²	+03 1.333 22
centimeter of water (4° C)	newton/meter²	+01 9.806 38
dyne/centimeter²	newton/meter²	−01 1.00*
foot of water (39.2° F)	newton/meter²	+03 2.988 98
inch of mercury (32° F)	newton/meter²	+03 3.386 389
inch of mercury (60° F)	newton/meter²	+03 3.376 85
inch of water (39.2° F)	newton/meter²	+02 2.490 82
inch of water (60° F)	newton/meter²	+02 2.4884
kgf/centimeter²	newton/meter²	+04 9.806 65*
kgf/meter²	newton/meter²	+00 9.806 65*
lbf/foot²	newton/meter²	+01 4.788 025 8
lbf/inch² (psi)	newton/meter²	+03 6.894 757 2
millibar	newton/meter²	+02 1.00*
millimeter of mercury (0° C)	newton/meter²	+02 1.333 224
pascal	newton/meter²	+00 1.00*
psi (lbf/inch²)	newton/meter²	+03 6.894 757 2
torr (0' C)	newton/meter³	+02 1.333 22

SPEED

foot/hour	meter/second	−05 8.466 666 6
foot/minute	meter/second	−03 5.08*
foot/second	meter/second	−01 3.048*
inch/second	meter/second	−02 2.54*

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To convert from	to	multiply by
kilometer/hour	meter/second	−01 2.777 777 8
knot (international)	meter/second	−01 5.144 444 444
mile/hour (U.S. statute)	meter/second	−01 4.4704*
mile/minute (U.S. statute)	meter/second	+01 2.682 24*
mile/second (U.S. statute)	meter/second	+03 1.609 344*

TEMPERATURE

Celsius	kelvin	$t_K = t_C + 273.15$
Fahrenheit	kelvin	$t_K = (5/9)(t_F + 459.67)$
Fahrenheit	Celsius	$t_C = (5/9)(t_F - 32)$
Rankine	kelvin	$t_K = (5/9)t_R$

TIME

day (mean solar)	second (mean solar)	+04 8.64*
day (sidereal)	second (mean solar)	+04 8.616 409 0
hour (mean solar)	second (mean solar)	+03 3.60*
hour (sidereal)	second (mean solar)	+03 3.590 170 4
minute (mean solar)	second (mean solar)	+01 6.00*
minute (sidereal)	second (mean solar)	+01 5.983 617 4
month (mean calendar)	second (mean solar)	+06 2.628*
second (ephemeris)	second	+00 1.000 000 000
second (mean solar)	second (ephemeris)	Consult American Ephemeris and Nautical Almanac
second (sidereal)	second (mean solar)	−01 9.972 695 7
year (calendar)	second (mean solar)	+07 3.1536*
year (sidereal)	second (mean solar)	+07 3.155 815 0
year (tropical)	second (mean solar)	+07 3.155 692 6
year 1900, tropical, Jan., day 0, hour 12	second (ephemeris)	+07 3.155 692 597 47*
year 1900, tropical, Jan., day 0, hour 12	second	+07 3.155 692 597 47

VISCOSITY

centistoke	meter²/second	−06 1.00*
stoke	meter²/second	−04 1.00*
foot²/second	meter²/second	−02 9.290 304*
centipoise	newton second/meter²	−03 1.00*
lbm/foot second	newton second/meter²	+00 1.488 163 9
lbf second/foot²	newton second/meter²	+01 4.788 025 8
poise	newton second/meter²	−01 1.00*
poundal second/foot²	newton second/meter²	+00 1.488 163 9
slug/foot second	newton second/meter²	+01 4.788 025 8
rhe	meter²/newton second	+01 1.00*

VOLUME

acre foot	meter³	+03 1.233 481 837 547 52*
barrel (petroleum, 42 gallons)	meter³	−01 1.589 873
board foot	meter³	−03 2.359 737 216*
bushel (U.S.)	meter³	−02 3.523 907 016 688*
cord	meter³	+00 3.624 556 3
cup	meter³	−04 2.365 882 365*
dram (U.S. fluid)	meter³	−06 3.696 691 195 312 5*
fluid ounce (U.S.)	meter³	−05 2.957 352 956 25*
foot³	meter³	−02 2.831 684 659 2*

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To convert from	to	multiply by
gallon (U.K. liquid)	meter³	−03 4.546 087
gallon (U.S. dry)	meter³	−03 4.404 883 770 86*
gallon (U.S. liquid)	meter³	−03 3.785 411 784*
gill (U K.)	meter³	−04 1.420 652
gill (U.S.)	meter³	−04 1.182 941 2
hogshead (U.S.)	meter³	−01 2.384 809 423 92*
inch³	meter³	−05 1 638 706 4*
liter	meter³	−03 1.00*
ounce (U.S. fluid)	meter³	−05 2.957 352 956 25*
peck (U.S.)	meter³	−03 8.809 767 541 72*
pint (U.S. dry)	meter³	−04 5.506 104 713 575*
pint (U.S. liquid)	meter³	−04 4.731 764 73*
quart (U.S. dry)	meter³	−03 1.101 220 942 715*
quart (U.S. liquid)	meter³	−04 9.463 529 5
stere	meter³	+00 1.00*
tablespoon	meter³	−05 1.478 676 478 125*
teaspoon	meter³	−06 4.928 921 593 75*
ton (register)	meter³	+00 2.831 684 659 2*
yard³	meter³	−01 7.645 548 579 84*

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